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Automated Planning for AERA 3: Maneuver Option Manager

Advanced System Design Service
Washington, D.C. 20591

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16. Abstract

This document describes Maneuver Option Manager (MOM), a methodology to simplify complex air traffic control (ATC) problems. A complex problem is identified here as a set of interrelated potential conflicts between pairs of aircraft. It may involve arbitrarily many aircraft. MOM determines which of six simple maneuver options is a available (free of such potential conflicts) for each aircraft. These options involve limited displacements left/right/ahead/behind/above/below nominal. MOM simplifies a complex problem by protecting (for future use) an available maneuver option for one or more of the involved aircraft. Routinely, a single such maneuver option resolves several potential conflicts. Iterated protection of maneuver options causes complex problems to be broken into independent, smaller, and simpler problems.

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ABSTRACT

This document describes Maneuver Option Manager (MOM), a methodology to simplify complex air traffic control (ATC) problems. A complex problem is identified here as a set of interrelated potential conflicts between pairs of aircraft. It may involve arbitrarily many aircraft. MOM determines which of six simple maneuver options is available (free of such potential conflicts) for each aircraft. These options involve limited displacements left/right/ahead/behind/above/below nominal. MOM simplifies a complex problem by protecting (for future use) an available maneuver option for one or more of the involved aircraft. Routinely, a single such maneuver option resolves several potential conflicts. Iterated protection of maneuver options causes complex problems to be broken into independent, smaller, and simpler problems.

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EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) is sponsoring research by The MITRE Corporation into air traffic control (ATC) automation to achieve goals such as increased safety, productivity, capacity, and improved services to public/pilots/airlines. Various automation aids for the controller will be introduced in several steps over the next twelve or so years. A final automation step is known as AERA 3, in which the human, for the first time, is no longer involved in routine or time-critical decisions ("AERA" stands for "Automated En-Route ATC").

A key feature of AERA 3 is Maneuver Option Manager (MOM), a methodology to simplify complex ATC problems. A complex problem is identified here as a set of interrelated possible pairwise separation problems (abbreviated possiblems) between aircraft. A complex problem may involve arbitrarily many aircraft and possiblems. The possiblems are predicted over a horizon of about thirty minutes.

MOM determines which of several simple maneuver options is available (free of such possiblems) for each aircraft. The maneuver options tested involve limited displacements left/right/ahead/behind/above/below nominal. The displacements from nominal typically begin some minutes in the future, generally a few minutes prior to the earliest possiblem being resolved.

Possiblem-free maneuver options are known as outs. By resolving outs for one or more of the involved aircraft, MOM simplies a complex problem, causing it to be broken into independent, smaller, and less complex problems. Routinely, a single out is used by MOM to resolve several possiblems.

By reserving or protecting certain outs for possible future use, MOM assures that simplifications exist for all complex problems, out to a rolling thirty-minute horizon, even when prediction uncertainties combine adversely. This MOM feature is expected to play a key role in AERA 3.

The MOM methodology allows a systems approach to ATC, not achievable solely via the traditional methodologies that consider either pairwise conflicts one at a time, or aggregate traffic flows.

SECTION 1

INTRODUCTION

This document discusses Maneuver Option Manager (MOM), a concept for simplifying complex air traffic control (ATC) problems involving interrelated possible separation problems among multiple aircraft.

1.1 BACKGROUND

The Federal Aviation Administration (FAA) is sponsoring research by MITRE into ATC automation to achieve goals such as:

- Improved services to public/pilots/airlines (i.e., fewer delays, avoidance of unnecessary maneuvers, ability to grant pilot-requested routes whenever possible).
- Increased airspace capacity and utilization.
- Increased safety.
- Increased productivity (more aircraft moved per person).

A major part of the ATC automation effort is Automated En Route ATC, or AERA [1, 2, 3]. AERA will enhance the current ATC system in three successive phases (AERA 1, 2, and 3). Each successive phase of ATC automation, through AERA 3, is expected to achieve the above goals to a greater degree.

1.2 PURPOSE AND SCOPE OF DOCUMENT

The document's primary purpose is to introduce the MOM concept, and its planned role in AERA 3, to a general audience, particularly members of the aviation community with interest in ATC automation. It is not assumed that the reader has detailed knowledge of the current ATC system.

Although research on many of AERA 3's functions has begun only recently, research on the MOM concept has been underway since 1985. The MOM concept, which lends itself to a natural algorithmic methodology, has been tested extensively in rapid prototype simulations, and has stabilized.

MOM has become known as a centerpiece of AERA 3; it is hoped that early documentation of MOM will help provide a basis of support for the central AERA 3 notion that a very high degree of ATC automation is feasible.

An additional purpose is to document certain results which may prove useful in the ongoing development of AERA 3.

The scope of this document is generally limited to presentation of the MOM concept and methodology, and the way that MOM is expected to be used in AERA 3. Discussion of the various individual algorithms comprising the MOM methodology is, for the most part, beyond the scope here. A brief overview is given of the MOM rapid prototype simulation. Discussion of many technical details (beyond the scope here) is found in an earlier document [4] (in which MOM is called by its original name, Option Monitor or OM). Additional documentation is planned as well.

1.3 ORGANIZATION OF DOCUMENT

Section 2 gives an overview of how ATC automation is expected to evolve, from today's system through AERA 1 and AERA 2. Section 3 gives a sketch of AERA 3 and its parts, including MOM. The focus is on the interface between MOM and certain AERA 3 functions which interact closely with MOM. Section 4 presents the main MOM ideas–maneuver options, outs, etc., and a method by which complex interrelated separation problems (clusters) can be simplified. Section 5 gives an overview of a rapid prototype simulation of MOM, and its results. Section 6 provides a summary.

Appendix A discusses tools that guarantee in certain situations that outs will become available in the future. Appendix B focuses on how, when, and to what degree MOM might commit AERA 3 to a particular simplification for a particular situation.

SECTION 2

PLANNED EVOLUTION OF ATC AUTOMATION

To place AERA 3 and MOM in context, a brief overview is given of the expected evolution of ATC from the current system up to AERA 3. Some of the material here is excerpted or paraphrased from [2], in which these topics are presented in more detail

2.1 TODAY'S ATC SYSTEM

In today's ATC system, there are three levels of activities to assure separation of aircraft: national, local, and sector. On a nationwide scale, traffic is monitored and flow restrictions are established as necessary so that traffic is manageable at the local level. At the local level, in turn, traffic is monitored and flow restrictions are established as necessary so that traffic in terminal and en route sectors is manageable. The three levels are analogous to three nested shells, each other shell protecting the next shell in, and the innermost assuring aircraft separation. Ultimate responsibility for aircraft separation rests with the sector controller. Currently, all three levels of management are performed manually with minimal automation aids.

The current en route ATC system has limitations which frequently make it difficult to grant or sustain user-preferred trajectories. Many of these limitations are inherent in the hardware and software of the ATC system. Other limitations are due to the manual and mental processing capabilities of a human being. Major limitations of the current system include:

- Inability to accept the full intent of the pilot.
- Separation standards geared to the human (e.g., the controller's view of the plan view display).
- Human error (e.g., inattention, forgetfulness, misinterpretation, stress, fatigue).

Many of these limitations can be overcome in various ways by automation. To help accomplish this, the FAA has developed the National Airspace System (NAS) Plan for modernizing and improving the ATC system. The next sections summarize the AERA-related portions of the plan.

2.2 AERA 1 AND CONCURRENT ATC ENHANCEMENTS

The first phase of AERA, AERA 1, includes basic computation of aircraft trajectories including pilot intent, and detection of potential violations of separation standards or of flow restrictions, both for existing aircraft flight plans, and for controller-designated alternate aircraft flight plans.

Additional enhancements to the ATC system available by the time of AERA 1, in the next few years, include capabilities such as:

- Replacement of the current computer system, relieving current capacity limitations.
- Automation aids to assist in spacing (metering) of aircraft.
- Automation aids at the national level to formulate traffic management strategies (the Advanced Traffic Management System, or ATMS).

2.3 AERA 2 ENHANCEMENTS

AERA 2 introduces many new capabilities, most importantly a list of computer-recommended resolutions to potential separation violations detected by AERA 1. AERA 2 also introduces automated controller coordination aids, and use of automated air-ground communication when available.

Ultimate responsibility for aircraft separation remains with the human sector controller under AERA 2, just as today.

SECTION 3

AERA 3 OVERVIEW, WITH EMPHASIS ON MOM AND FUNCTIONS INTERACTING WITH MOM

In AERA 3 the automation assumes, for the first time, the responsibility of separating aircraft. AERA 3 is expected to allow denser traffic and to provide increased services to users than is possible under prior phases of ATC automation.

The human retains a role in formulating long-term strategies and traffic flow patterns, but does not in general deal with individual aircraft. The human (for the first time) is no longer involved in routine or time-critical separation assurance decisions.

As in the current system, ATC in the AERA 3 time frame (around the year 2000) will be hierarchical, so that the nested shell analogy (from Section 2.1) holds. At the national level, ATMS will remain in place (as the outermost shell), to keep traffic flow to a level that can be handled by AERA 3.

3.1 OUTER SHELL IN AERA 3

The next shell inward from ATMS is AERA 3's outermost shell, known as the Airspace Manager Planning Functions (Figure 3-1). These functions are automation aids to be used by a human (known as the Airspace Manager). This shell is loosely analogous to today's local flow management, but includes some new capabilities and is currently under development at MITRE.

The Airspace Manager Planning Functions generally deal with aircraft on an aggregate or statistical basis. The lookahead period, which extends out to perhaps 90 minutes, is large enough that prediction uncertainties preclude detailed analysis of specific aircraft-to-aircraft interactions.

Among the planning functions in this outer shell of AERA 3, Density/Complexity Manager has the closest interaction with MOM. It determines regions where traffic is expected to be unacceptably dense or difficult to manage (complex), and resolves such problems by maneuvering traffic. A key factor in determining what traffic is too dense or too complex is whether MOM is able to handle it.

3.2 MOM AS AN INTERMEDIATE AERA 3 SHELL

MOM is planned as the next inner shell in AERA 3. MOM generally looks five to thirty minutes ahead, when possible separation problems between pairs of aircraft can be profitably detected, analyzed and placed in a global context, but when prediction uncertainties can preclude either (a) final determination of which possible pairwise separation problems will actually require aircraft to be maneuvered, and (b) routine determination of the best resolutions for specific possible pairwise separation problems.

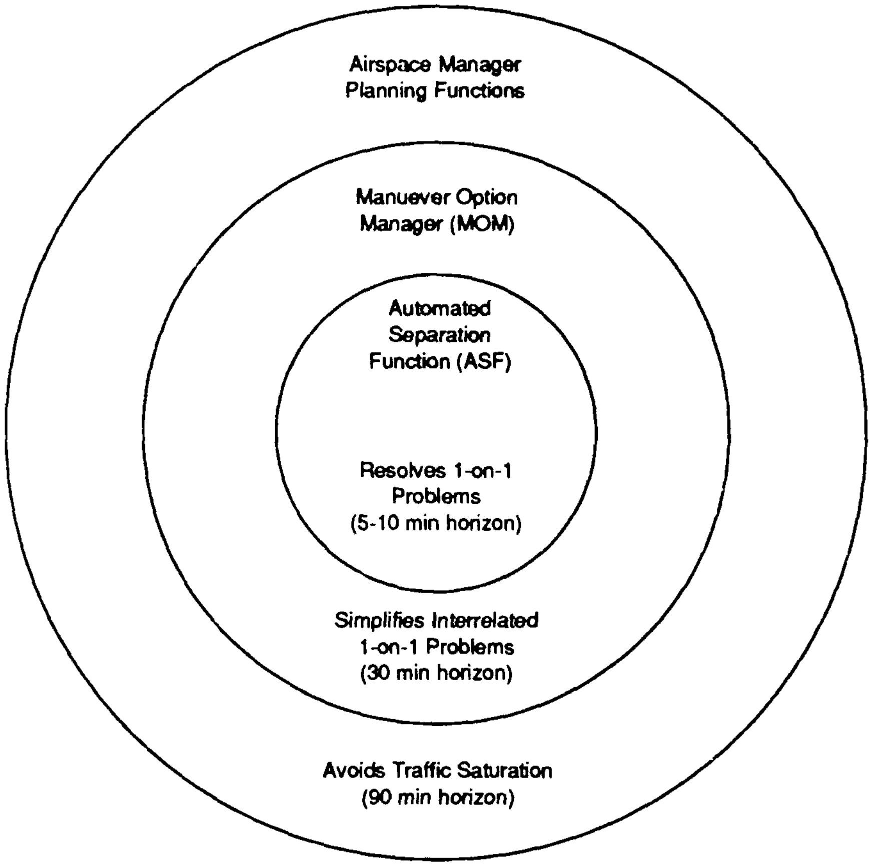

FIGURE 3-1
AERA 3 NESTED SHELLS

3.2.1 Possible Pairwise Separation Problems (Possiblems)

Possible pairwise separation problems are a key part of the MOM concept. For convenience (and to emphasize via a coined word the fact that the idea is not used in ATC now), the four-word phrase is abbreviated "possiblem". The focus in this document is mainly on aircraft-to-aircraft possiblems, but the term also encompasses other possible pairwise separation problems (e.g., aircraft-to-airspace).

3.2.2 Clusters

A set of possiblems involving a set of aircraft is defined as a cluster, another key MOM idea. For example, possiblems between Aircraft A and B, and between B and C, are said to form a three-aircraft, two-possiblem cluster. A separate cluster might involve four other aircraft (say, D, E, F, and G), with five possiblems (say, D-E, D-F, D-G, E-F, and F-G).

3.2.3 Available Maneuver Options (Outs)

MOM determines which of several simple maneuver options is available (free of possiblems) for each aircraft. These options involve limited displacements left/right/ahead/behind/above/below nominal. The displacements are modeled to begin not immediately, but typically some minutes in the future, usually just a few minutes prior to the possiblems.

An available maneuver option eliminates all of an aircraft's possiblems, and causes no new ones (assuming the other aircraft maintain their trajectories within a tolerance).

An available maneuver option is also known (for simplicity) as an out.

3.2.4 Simplification of Clusters

MOM simplifies a cluster by protecting (for future use) an out for one or more of the involved aircraft. The future use of the out causes a cluster to be broken into independent, smaller, and less complex clusters.

For instance, an out for Aircraft D in the above example would eliminate three of the cluster's five possiblems (the three involving D), thereby reducing the cluster to two possiblems (both involving F). A second out (for F) eliminates the remaining two possiblems. No new possiblems are created versus any other aircraft; however, a separate check must be made that D's and F's outs are compatible with each other and do not result in a D-F possiblem.

3.2.5 Contingency Plan

MOM maintains at all times a contingency plan, consisting of a set of outs that provide safe separation between all pairs of aircraft . The contingency plan simplifies all clusters to a level necessary to ensure that AERA 3's inner shell can resolve any remaining separation problems. This level may consist of isolated possiblems whose aircraft have outs, though somewhat less simple situations may be tolerated at MOM's longer lookaheads.

3.2.6 Designated Outs

Occasionally, MOM identifies, or designates, a particular out as providing enough planning benefits that AERA 3 should commit early to it (to some degree), despite the fact that more accurate information will in become available in the future. An out may be designated in general terms, or as a specific maneuver. An active area of research is to determine which outs to designate. Attractive candidates are outs which resolve many possiblems at once, especially possiblems with high certainty of requiring a separation maneuver.

3.3 INNER SHELL IN AERA 3

The innermost AERA 3 shell is the Automated Separation Function (ASF) (Figure 3-1). ASF is loosely analogous in purpose to today's ATC at the sector level. ASF has several parts, but its main purpose is to determine detailed resolutions for specific pairwise separation problems (aircraft versus aircraft or airspace). It seeks resolutions which are safe and which impose minimal penalty upon the aircraft (time, fuel, etc.). Its lookahead is less than ten minutes, over which prediction uncertainties are relatively small. It uses track-based data as well as trajectory data (whereas all outer shells use primarily trajectory data).

ASF generally considers pairwise separation problems one (or a very few) at a time, an approach that is justified from a system planning point of view given that MOM breaks down clusters involving multiple interrelated possiblems. ASF relies upon input from MOM to rule out classes of maneuvers with adverse downstream effects on other traffic. ASF respects designated outs but is expected to improve on MOM's contingency plan (as long as an alternate contingency plan can be found at each step). Well after MOM designates an out in general terms, ASF determines the specifics using the latest track data.

3.4 AERA 3 NESTED SHELLS IN CONTEXT

The hierarchy of nested shells in AERA, shown in Figure 3-1, works as follows:

- ASF separates aircraft.
- MOM assures that ASF can operate successfully in a global context (though ASF considers pairwise separation problems one at a time).

- The Airspace Manager Planning Functions (particularly Density/Complexity) assures (among other things) that MOM can operate successfully (e.g., by preventing traffic densities that cause aircraft to have too few outs).

- ATMS, on a national level, assures that the Airspace Manager Planning Functions (and thereby, all of AERA 3) can operate successfully.

It is expected that ASF and MOM will be entirely automated, while the outer shell will be an automation aid to the Airspace Manager.

3.5 AERA 3 FUNCTIONS OUTSIDE THE NESTED SHELL HIERARCHY

It should be noted that AERA 3 includes functions that cut across the hierarchy described above. For example, AERA 3's Time-based Spacing function assures that aircraft which must arrive at a particular location in a time sequence do so expeditiously and safely; action at both long and short lookaheads is involved. Other examples include "core" AERA 3 functions, such as generation of trajectories, and functions which deal with detection and handling of exceptional situations, such as an aircraft which has lost radio communications. These parts of AERA 3 outside the nested shell hierarchy will not be discussed further in this document.

3.6 HOW TODAY'S ATC SYSTEM ACCOMPLISHES MOM'S GOAL OF SIMPLIFYING COMPLEX PROBLEMS

There is no automation capability in the current ATC system, or under enhancements through AERA 2, that is analogous to MOM. Today's ATC succeeds (without a MOM capability) due to (a) sector controller expertise at resolving smaller and/or simpler clusters (involving several aircraft), and (b) flow controller expertise and conservatism at preventing the occurrence of larger and/or more complex clusters (via structuring traffic). Both (a) and (b), while safe, often result in unnecessary time and fuel costs to aircraft.

MOM helps to bridge what has heretofore been a gap between (1) ATC functions oriented toward solving individual separation problems one at a time, and (2) longer-lookahead ATC functions oriented toward aggregate traffic flows or statistical analysis.

SECTION 4

A MORE DETAILED DESCRIPTION OF MOM

This section presents a somewhat more detailed description of the MOM methodology, enlarging on the sketch from Section 3.2.

Section 4 expands on the material presented in Sections 3.2.1 through 3.2.4; topics include:

- Detection of possiblems (Section 4.1).
- Detection of constraints on maneuver options (Section 4.2).
- Detection of outs (Section 4.3).
- Detection of clusters (Section 4.4).
- Graphic representation of clusters (Section 4.5).
- Generic simplification of clusters (Sections 4.6-4.7).

"Generic simplification of clusters," as used here, encompasses means by which MOM finds any one of a large number of possible ways to simplify a given cluster. It does not encompass issues involving selecting a particular simplification--e.g., how to select a contingency plan, and when to designate an out (this material, discussed in some detail in Appendix B, expands upon material presented in Sections 3.2.5 and 3.2.6).

4.1 DATA INPUT TO MOM

MOM's primary input is, for each aircraft, a trajectory (a path in xyzt space), which each aircraft is expected to follow to within some specified plus/minus tolerance (laterally, vertically, and in time). Tolerance size may depend on planned maneuvers and on the lookahead time. MOM examines trajectory data only out to some future time (the lookahead horizon), perhaps thirty minutes from the current time, beyond which trajectory data is not accurate enough to support MOM processing. (Other AERA 3 processing will, as mentioned above, look farther into the future than this.)

4.2 DETECTING POSSIBLEMS AND CONSTRAINTS ON OPTIONS

Detection of possiblems and detection of constraints on options are closely related tasks: detection, respectively, of whether an aircraft's current trajectory, or the trajectory modified by some displacement from nominal, could possibly come close enough to another aircraft's current trajectory to require a future ATC separation maneuver.

4.2.1 Detecting Possiblems

To determine whether two aircraft form a possiblem, the nominal position of each aircraft, which moves as a function of time, is surrounded by a box. The two aircraft form a possiblem if the two boxes ever bump.[1]

The box reflects both the uncertainty in the aircraft's predicted position, and a buffer to assure safe separation. It is useful to envision two nested boxes. Each aircraft is expected to stay within its inner box; if the outer buffered boxes for two aircraft do not bump, the inner boxes (that is, the aircraft themselves) must be safely separated (Figure 4-1a).

Predicted position uncertainty is a result of such factors as uncertainties in predicted winds and temperatures, aircraft performance limitations, imprecise timing of future maneuvers, etc. Generally, the uncertainties grow with increasing lookahead (particularly in the box's along-route dimension). A key open issue involves determining the size of the boxes and their rate of growth with increasing lookahead.

4.2.2 Detecting Contraints

Likewise, to determine if Aircraft B prevents Aircraft A from being safely displaced m units left/right/ahead/behind/above/below nominal, one determines whether such a displacement would cause an (A versus B) possiblem, using uncertainty boxes as above.

Figure 4-lb illustrates the detection of constraints. It is similar to Figure 4-la, except that additional regions left, right, ahead, behind, above and below have been appended to Aircraft A's box. As this object and B's box move forward in time, some of the regions appended to A's box will bump B's box; the direction of displacement from nominal (that is associated with any such region) is constrained for A by B.[2]

A typical constraint (as determined at, say, time 0:30) on one aircraft's option due to another aircraft has the following form:

- Aircraft i cannot be 18-30 nmi RIGHT of nominal, during times 0:34-0:35, due to Aircraft j.

[1]To determine whether two boxes (that move and grow over time) ever bump can be accomplished via a linear program, whose variables are the space-time coordinates x,y,z, and t. The box sizes are a function of the longitudinal, lateral, and vertical uncertainty, and the minimal separation tolerated between the aircraft.

[2]Using a fifth variable m (in addition to x,y,z,t), to represent magnitude of displacement from nominal, a modified linear program can detect constraints by one aircraft upon another over a range of possible displacements from nominal in a given direction.

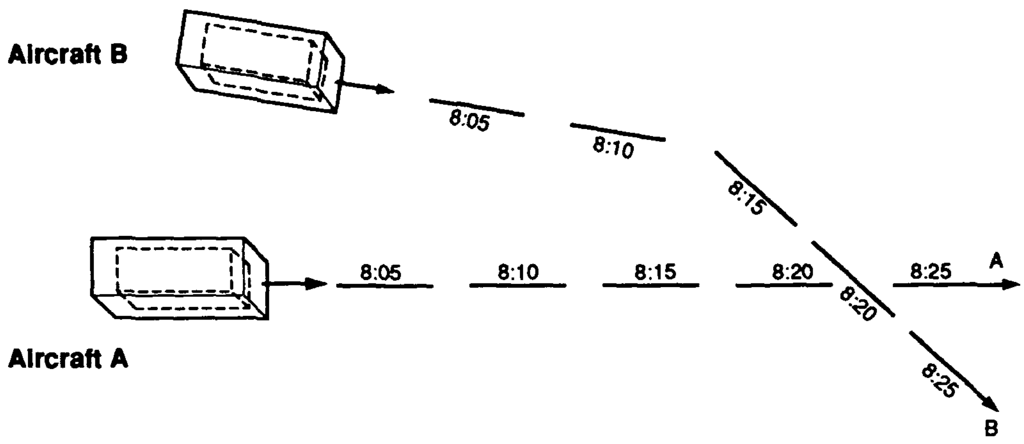

FIGURE 4-1a
A POSSIBLE PAIRWISE SEPARATION PROBLEM (POSSIBLEM) EXISTS IF BUFFERED BOXES ABOUT EACH AIRCRAFT, MOVING IN TIME, EVER BUMP

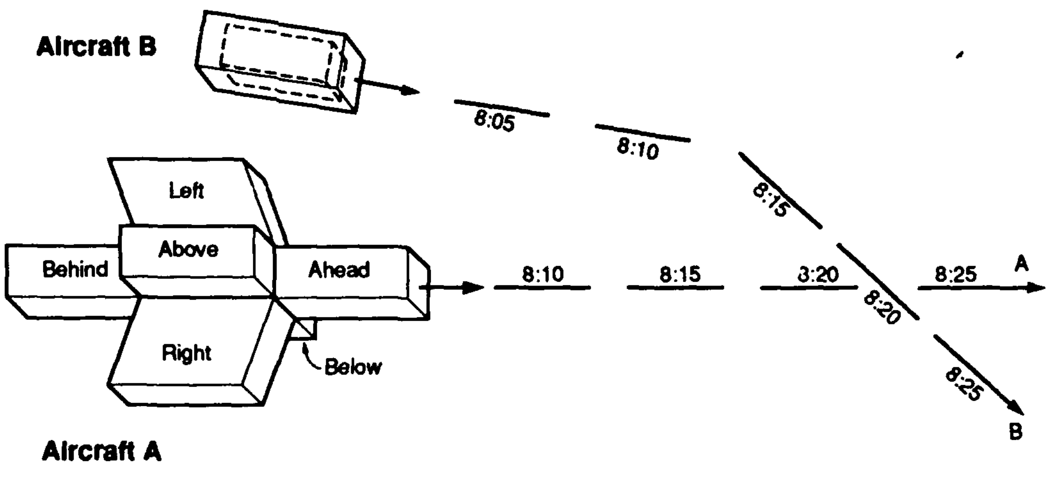

FIGURE 4-1b
A's VARIOUS MANEUVER OPTIONS ARE CONSTRAINED BY B IF THE CORRESPONDING REGIONS ATTACHED TO A's BOX EVER BUMP B's BOX

It is often convenient to make a Cartesian plot of all the constraints on all the options of a given aircraft. The axes are time (t), by convention plotted vertically, and displacement magnitude (m), plotted horizontally. The leftward constraint of B upon A would be represented by a rectangle covering values of (m, t) where 18 <= m <= 30 and 0:34 <= t <= 0:35.

An example of this type of Cartisian plot, called a constraint graph, is given in Figure 4-2. There are actually three separate Cartesian plots, one for left/right options, one for slow/fast options, and one for below/above options.

The vertical axis on each of the three plots represents m = 0, or no displacement from nominal. By convention, left, behind, and below are represented by negative values of m, while right, fast, and above are represented by positive values of m. The 18-30 nmi constraint on the RIGHT option can be seen (here, F is the constrained aircraft and B is the constraining aircraft). Other constraints on F due to two other aircraft (A and C) are also shown.

The vertically-hatched regions represent values of (m, t) that cannot be attained by the aircraft via 30-degree turns, 50-knot slowdowns, 40-knot speedups, 2000 foot-per-minute descents, and 1000 foot-per-minute climbs (these parameters will ultimately be determined according to aircraft performance and user preferences).

4.3 DETECTING OUTS

An out is a maneuver involving a displacement of m units from nominal in a given direction that is free of constraints due to any other aircraft, over the specified lookahead horizon.

More formally, Aircraft i has out u (u = LEFTWARD, RIGHTWARD, ABOVE, BELOW, AHEAD, or BEHIND) if there exists a distance m such that:

- Aircraft i is free of possiblems versus all aircraft, over the specified lookahead horizon, when a displacement of m units in direction u is incorporated into i's trajectory.

with the following provisos:

- The displacement is modeled in a realistic fashion (e.g., achieving a parallel lateral offset of m units leftward, say, must induce an along-route delay proportional to m).

- Aircraft i can transition to displacement m, at reasonably gentle accelerations, by the time of i's first possiblem, without the introduction of new possiblems.

- The value of the displacement m is bounded by some limit (in the figure, 30 miles for left/right options, 6000 feet for above/below options, etc.).

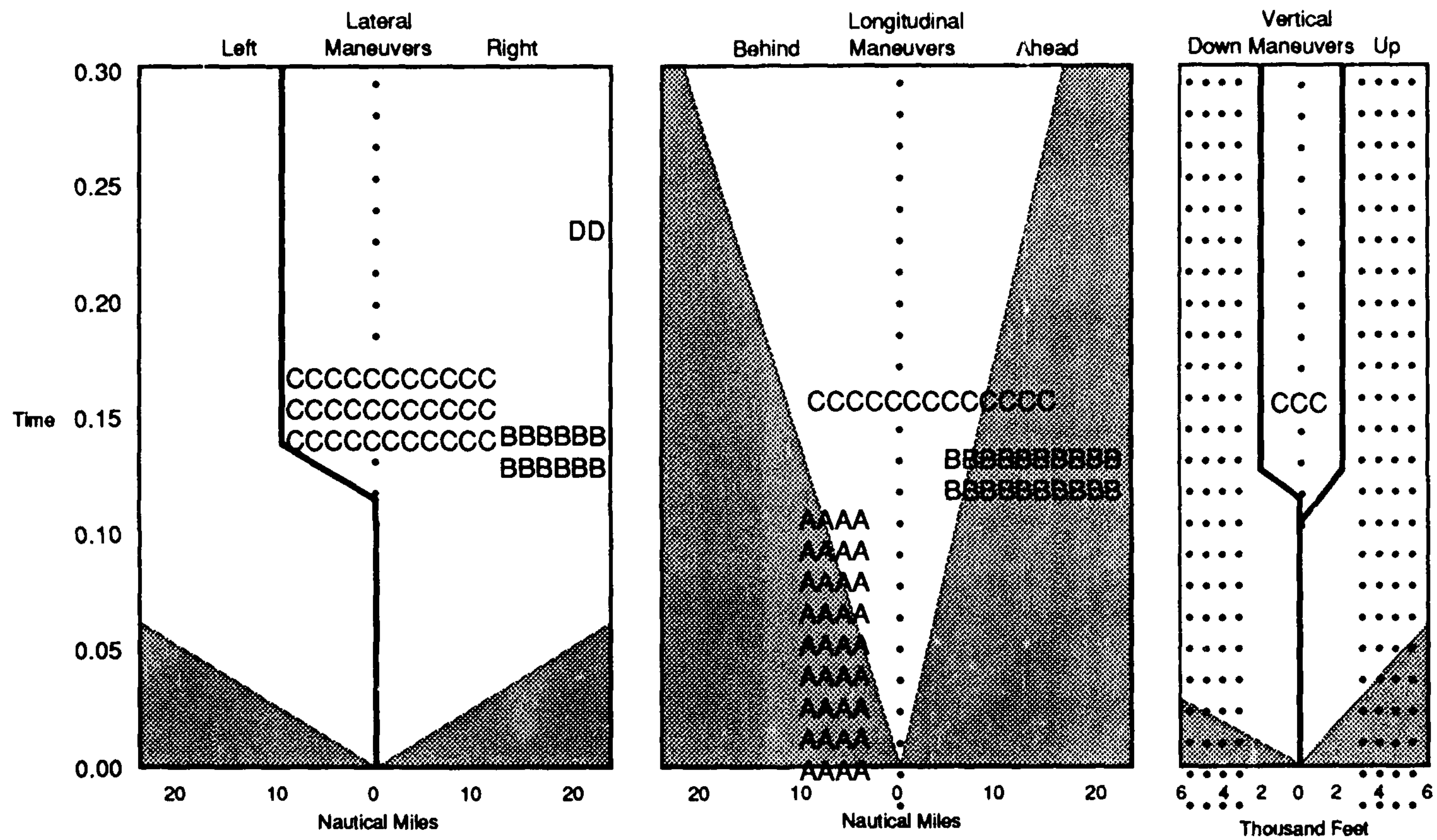

FIGURE 4-2
CONSTRAINT GRAPH FOR AIRCRAFT F

- The option is not constrained for some non-traffic reason, such as a bad weather area, a military area, or a performance limitation (e.g., an aircraft might not be able to climb or speed up).

An out can usually be detected via a glance at the constraint graph: first, an empty column (i.e., free of constraints) must exist for some value of m, say m', that extends to the lookahead horizon; second, a connecting (empty, constraint-free) corridor from displacement m = 0 to displacement m = m' that extends long enough in time for the aircraft to achieve the displacement (about 2, 1, and 2 minutes respectively, for the three outs LEFT (10 nmi), BELOW (one FL), and ABOVE (one FL), shown in Figure 4-2).

In the figure, the three thick lines show the values of (m, t) if the aircraft follows these three outs. In each case, the aircraft stays on nominal until about 0:33, achieves the full offset (left, below, or above) at about 0:35, and continues at the offset thereafter. Note that a BEHIND out is not available for F, since F cannot reach the empty column (at 12 nmi behind nominal) via a 50-knot slowdown (F would have to wait until 0:29 to clear A, then slow down by about 70 knots to get behind C at 0:36).

Once an aircraft is clear of possiblems via an out, it may (as modeled by MOM) either remain at its offset indefinitely, or gradually return to nominal.

4.4 DETERMINING CLUSTERS

To determine clusters, given a scenario's set of aircraft and set of possiblems, one starts with an arbitrary aircraft with possiblems, say Aircraft i. The aircraft in i's cluster are:

- Those aircraft having possiblems with i (denoted Set i')
- Those aircraft having possiblems with aircraft in Set i' (denoted Set i")
- Those aircraft having possiblems with aircraft in Set i" (denoted Set i"')
- Etc.

If any aircraft with possiblems remain (i.e., any that are not yet assigned to a cluster), one of them is picked arbitrarily to fill the role of i above, and a second cluster is determined, in a similar fashion. Determination of clusters continues until all aircraft with possiblems are assigned to a cluster.

A cluster may have as few as two aircraft (an isolated possiblem), or may have arbitrarily many aircraft.

It is possible that two aircraft (say A and B) are in the same cluster, but A and B themselves do not form a possiblem. In this case, A and B may never come within fifty or a hundred miles (just as a

person may not know his friends' friends or friends' friends' friends). In this respect, our usage of the term "cluster" differs somewhat from the word's typical usage by air traffic controllers today (where all members of a cluster do come close).

It is sometimes useful to distinguish clusters which involve nearly-simultaneous possiblems from those involving possiblems over a longer period (e.g., MOM's lookahead horizon). These are sometimes called microclusters and macroclusters, respectively. Either type of cluster is detected in the same way, except that the set of possiblems would include only those whose lifetimes overlap the time interval of interest. For instance, a 6-aircraft, 8-possiblem macrocluster (over MOM's lookahead horizon) may contain four possiblems about 15 minutes from the current time, and four more 25-30 minutes from the current time; these two four-possiblem microclusters may be usefully considered as units.

4.5 CLUSTER GRAPH

It is helpful to illustrate clusters using a graph, in which aircraft are represented as nodes, and possiblems as edges between nodes. If each aircraft in a scenario has a node, clusters as defined above correspond to connected subgraphs. Normally one considers the graph of one cluster at a time.

Figure 4-3a shows an example cluster involving 15 aircraft and 15 possiblems. One can see that:

- Three aircraft (C, H, K) have three possiblems
- Nine aircraft have two possiblems
- Three aircraft (A, N, O) have one possiblem

The position of the nodes on the graph is arbitrary and is unrelated to aircraft positions or velocities.

It is worth noting that a cluster graph can represent possiblems other than those between two aircraft. For instance, Node I might represent a military airspace, into which penetrates the trajectories of Aircraft H and J. This penetration represented by edges H-I and I-J. For simplicity, however, only aircraft-aircraft possiblems will be discussed from here on in this document.

In computer simulations, it is often useful to illustrate the microclusters within a macrocluster via animation of the cluster graph. For example, the edges in the cluster graph that corresponds to possiblems over the period 0-5 minutes from now could be displayed first, then those 1-6 minutes from now, then 2-7 minutes, etc. In such an animation, each microcluster is readily observed, as it forms, evolves, and dissipates.

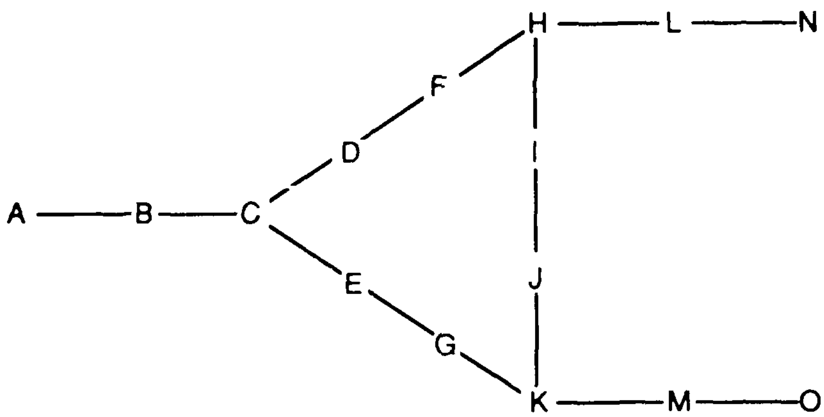

FIGURE 4-3a
A 15-AIRCRAFT, 15-POSSIBLEM CLUSTER

4.6 USE OF OUTS TO SIMPLIFY CLUSTERS

Simplification of clusters generally involves using, or more commonly, protecting for possible future use, one or more outs for aircraft involved in the clusters.

"Use an out", in Sections 4 and 5, refers not to determining a particular or "best" simplification for a cluster, but rather to generic simplification of clusters–i.e., selection of any of multiple possible simplifications. Discussion of issues such as which simplification should be chosen for the contingency plan, or which outs should be designated, is deferred to Appendix B.

Suppose a single aircraft, i, is maneuvered, and the maneuver used is an out. Also, suppose all other aircraft stay on their trajectories to within their tolerances. Then the following equivalent statements are true:

- All of aircraft i's possiblems are eliminated, and no new ones are created.
- All edges touching Aircraft i's node in the graph are eliminated, and no new edges are added.

Both results follow immediately from the definition of an out (i.e., of an available maneuver option) in Section 4.3. *If a possiblem (say, aircraft i versus aircraft j) would exist if i is displaced m units via* one of its six options (left/right/ahead/behind/above/below), that option for i would have been constrained by j, and hence would not have been available for i.

In the Figure 4-3a scenario, an attractive strategy might be to use an out for each of the three aircraft (C, H, K) with three possiblems each. The idea is to simplify the cluster from 15 interrelated

possiblems to six isolated possiblems, as shown in Figure 4-3b. ASF (AERA 3's innermost shell) readily deals with the six isolated simple possiblems.

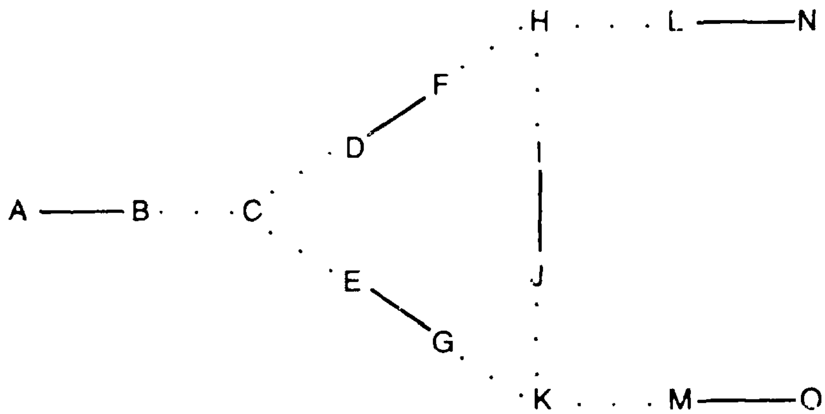

FIGURE 4-3b
USE OF OUTS FOR THREE AIRCRAFT (C, H, K)
SIMPLIFIES CLUSTER TO SIX UNRELATED POSSIBLEMS

As seen in the next section, however, an additional check must be made, to determine whether possiblems among the three maneuvered aircraft (C, H, K) might be introduced.

4.7 ISSUES INVOLVING USE OF MORE THAN ONE OUT

As long as the use of only a single out is contemplated, one may expect the out to eliminate all the possiblems involving the maneuvered aircraft and to introduce no new possiblems for any aircraft.

When simultaneous use of two or more outs is contemplated, new possiblems may be introduced–but only possiblems between maneuvered aircraft. For example, suppose Aircraft P and Q have a possiblem at FL 370 (37,000 feet), and, two flight levels below at FL 330 (33,000 feet), Aircraft R and S have a possiblem. Suppose that a below out is available for Aircraft P, as is an above out for Aircraft R. If both outs are used simultaneously, Aircraft P and R may have a possiblem at the intermediate flight level FL 350.

This phenomenon is rarely more than a minor nuisance for MOM, for the following reasons (the items below reference the simultaneous use of outs for Aircraft C, H, and K in Figure 4-3, as discussed at the end of the previous section):

- It is quite likely that Aircraft C, H, and K are nowhere near each other, or that they may be reasonably near but the particular outs do not force them nearer. C simply has a possiblem with an aircraft which has a possiblem with an aircraft which has a possiblem with H; ditto for C and K, and for H and K.

- If a single possiblem (C-H, C-K, or H-K) is introduced, it is independent of the other six possiblems (A-B, D-F, E-G, I-J, L-N, M-O); MOM reduces the large cluster to seven instead of six isolated possiblems.

- If two possiblems are introduced (say, C-H and C-K), the use of an alternative out for any one C, H, or K will likely allow a solution with zero or one introduced possiblems.

- In the worst case, all three possiblems are introduced (C-H, C-K, H-K). Still, nine of the original fifteen possiblems were eliminated, leaving a total of 15-9 + 3 = 9 possiblems, a net elimination of six.

- MOM has other alternatives than maneuvering (C, H, K). Possibilities include using outs for each of (D, E, H, and K), or for each of (C, H, G and J), or for each of (C, F, I and K).

Simulation results indicate that a general criterion for whether a cluster can be simplified via outs is that most aircraft have at least one out, and that some aircraft have more than one.

Often, however, MOM can tolerate a few aircraft in a cluster with no outs. Nearby aircraft with outs often can be moved out of the thick of things, thereby creating outs for the no-out aircraft.

4.8 TOOLS TO GUARANTEE THAT OUTS WILL BECOME AVAILABLE IN THE FUTURE

MOM specifies each out as a particular magnitude of displacement from nominal. It is useful, however, for MOM to be cognizant of situations where an out is guaranteed to become available, but the exact magnitude of the displacement (or even the direction, such as left versus right) is not yet predictable.

Two methodologies to determine such situations are presented in Appendix A. They are known as Gentle-Strict (GS) (Section A.1), and Future Outs (Section A.2).

SECTION 5

MOM SIMULATION AND RESULTS

A rapid prototype simulation of MOM (about 50,000 lines of Pascal code) has been programmed on an Apollo workstation. Its purposes include:

1. Verify and test MOM's capability to simplify clusters, using a variety of air traffic scenarios, including:

   a. Traffic scenarios typical of those observed today (e.g., a set of 78 flight plans recorded near Gordonsville Sector, Washington Center, during one hour on May 15, 1985).

   b. Traffic scenarios modeled for the year 2000 (e.g., one based upon the 1985 scenario, but with traffic density increased by about 80 percent).

   c. Scenarios created artificially, in order to stress the logic.

2. Develop expertise in selecting particular sets of outs which simplify clusters:

   a. Manually.

   b. By means of an automated set of rules.

3. Investigate MOM's interface with AERA 3's inner and outer shells:

   a. Requirements by the inner shell upon MOM.

   b. Requirements by MOM upon the outer shell.

To date, (1) has been accomplished, as has much progress toward (2a). Progress on (2b) and (3) is just beginning.

5.1 HOW THE MOM SIMULATION IS USED

Upon beginning a MOM simulation session, the analyst first selects a scenario, as well as various parameters such as the predicted position uncertainty, a starting time, and the lookahead horizon. The simulation then uses a linear programming algorithm to detect, for each aircraft, all constraints on maneuver options imposed by all other aircraft over the lookahead horizon. Next, the simulation automatically determines all the possiblems, clusters, and outs. The analyst manually selects a set of outs to simplify the clusters, and then advances the simulation clock (e.g., by five or ten minutes). The chosen outs are incorporated into the trajectories; the lookahead horizon is extended, and the

process is repeated. The constraints, possiblems, clusters and outs are once again determined automatically, a new set of outs is manually selected, and the clock advanced again. Via repeated testing, various strategies for manually selecting outs can be compared, and expertise is built up.

The simulation displays upon request:

1. The node-edge graph for any specified cluster (similar to Figure 4-3a).

2. A four-dimensional view of the trajectories of the aircraft involved, including such features as zooms, rotates and movies (the time dimension is color-coded).

3. A graph of constraints and outs (similar to Figure 4-2) for any specified aircraft.

5.2 SIMULATION RESULTS

The basic MOM concepts discussed here have been verified. Several different analysts, using a variety of strategies to select outs, have successfully simplified all clusters in numerous air traffic scenarios, including the 1985 and the 2000 scenarios. Clusters involving up to ten and twenty aircraft was observed, respectively, in those two scenarios.

As traffic density increases, and aircraft with multiple possiblems but no outs become increasingly frequent, such aircraft often have maneuver options which fail to qualify as outs because of constraints by only one or two aircraft. In many instances it has proven effective to begin the simplification process with such maneuver options, which typically resolve five or six possiblems at the cost of introducing one or two possiblems.

5.3 NEXT STEPS

The next major goals are to achieve (2b), (3a), and (3b) above-that is, (2b) to automate the selection of simplifications for clusters, (3a) to analyze the interface between MOM and the inner shell, and (3b) to analyze the interface between MOM and the outer shell.

To automate simplification strategies (item (2b)), the first step planned is to compute simple weighted averages of some of the measures by which an out is evaluated (see Appendix B). Without human intervention, the simulation will select the highest-scoring outs, advance the clock, and evaluate its own performance (in terms of fuel and time cost of the maneuvers, and their effectiveness in simplifying clusters). Eventually, an expert system may be implemented to select outs.

To analyze MOM's interfaces, experiments are planned involving rapid prototype simulation of AERA's inner and outer shells (under concurrent development at MITRE). For instance, various simplifications, generated under many candidate MOM strategies, for clusters in air traffic scenarios, will be input to the ASF simulation; the overall AERA 3 performance would depend upon the union of the MOM- and the ASF-selected maneuvers. For the MOM-outer shell interface, scenarios too

dense for MOM to handle will be input to the outer shell simulation, which (using various candidate strategies) will attempt to reduce the density to a level MOM can handle (as cross-checked via the MOM simulation). There are many open issues to be addressed, including not only what set of maneuvers to select but also when to make the decision, and which of the three shells should make the decision in given circumstances.

SECTION 6

SUMMARY

The FAA is sponsoring research by The MITRE Corporation into ATC automation to achieve goals such as increased safety, productivity, ATC capacity, and improved services to public/pilots/airlines. Various automation aids for the controller will be introduced in several steps over the next twelve or so years. A final automation step is known as AERA 3, in which the human (for the first time) is no longer involved in routine or time-critical decisions.

A key feature of AERA 3 is Maneuver Option Manager (MOM), a methodology to simplify complex ATC problems. Complex problems, known in MOM terminology as clusters, are identified as sets of interrelated possible pairwise separation problems (or possiblems) between pairs of aircraft. A cluster may involve arbitrarily many aircraft and possiblems. Possiblems are detected out to about thirty minutes in the future.

MOM determines which of several simple maneuver options is available (free of such possiblems) for each aircraft. The maneuver options tested involve limited displacements left/right/ahead/behind/above/below nominal. Possiblem-free maneuver options are known as outs. The displacements from nominal typically begin some minutes in the future, generally a few minutes prior to the earliest possiblem being resolved. By reserving outs for one or more of the involved aircraft, MOM simplifies a complex problem (cluster), causing it to be broken into independent, smaller, and less complex problems. Routinely, a single maneuver is used by MOM to resolve several possiblems.

MOM assures that simplifications exist for all clusters, out to a rolling thirty-minute horizon, even when prediction uncertainties combine adversely. This MOM feature is expected to play a key role in helping to verify AERA 3 for operational use.

The MOM methodology allows a systems approach to automated ATC, not achievable solely via the traditional techniques that either consider pairwise conflicts one at a time, or aggregate traffic flows.

APPENDIX A

TOOLS TO GUARANTEE THAT OUTS WILL BECOME AVAILABLE IN THE FUTURE

MOM normally specifies an out in terms of a particular magnitude of displacement from nominal. It is useful, however, for MOM to be cognizant of situations where an out is guaranteed to become available, but the exact magnitude of the displacement (or even the direction, such as left or right) is not yet predictable.

Two methodologies to determine such situations are presented here. They are known as Gentle-Strict (GS) (Section A.1) and Future Outs (Section A.2).

A.1 GENTLE-STRICT (GS) METHODOLOGY AND MOM

Gentle-Strict (GS) is an AERA 3 methodology which resolves one-on-one conflicts between aircraft. Though other algorithms have been proposed for this purpose, GS uniquely facilitates quantitative analysis of the links between pairwise conflict resolution and longer lookahead air traffic control (ATC) strategies. In particular, there is a symbiosis between GS and MOM.

The GS methodology is presented in full in [5], as well as a detailed account of the symbiosis between GS and MOM. Both topics are summarized briefly here.

A.1.1 Outline OF GS Methodology

GS relates parameterizations of the following items (concerning an aircraft-to-aircraft possiblem) via a closed-form mathematical formula:

a. The encounter geometry (e.g., encounter angle, relative speed, relative timing to intersection; trajectories are assumed linear).

b. The minimum separation achieved.

c. The uncertainty in the aircraft predicted positions during the conflict.

d. The "gentleness" of the resolution maneuver (assumed to be a parallel lateral offset, and which begins only a few minutes prior to closest approach); gentleness is parameterized by:

   1.) Magnitude of the parallel lateral offset (nmi).

   2.) Along-route delay induced by the parallel offset.

Given minimum desired separation (b) and uncertainties (c), for instance, one can determine bounds on gentleness (d) as a function of encounter geometry (a). This application of the GS methodology is useful to AERA 3's inner shell, ASF, to determine (for prompt unlink to one of the aircraft) the gentlest parallel offset maneuver which safely resolves a conflict a few minutes in the future.

Or, given (b) and (c), one can determine what subset of the state space of encounter geometries (a) is resolvable via parallel offset maneuvers meeting a given bound on gentleness (d). It is this application of the GS methodology that is of particular use to MOM.

For instance, using a `inimum desired separation of 5 miles, and along-route uncertainties of ±1 mile (over five minutes lookahead), all linear geometries whose encounter angle exceeds 45 degrees, or whose relative speed (slower aircraft's speed/faster aircraft's speed) < 0.8, can be resolved by a parallel offset maneuver which does not exceed 12 nmi left/right of nominal and which does not delay the maneuvered aircraft by more than approximately 16 seconds.

A.1.2 How MOM Applies GS Methodology

The usefulness of GS to MOM lies in the fact that GS's mathematical relationship between (a), (b), (c), and (d) are calculable offline, if one substitutes:

i. the most pessimistic possible relative timing to intersection

for

ii. the predicted relative timing to intersection (in (a)).

The predicted relative timing is the only parameter in (a), (b), (c), and (d) that is predictable with significantly more accuracy minutes ahead (inner shell) than tens of minutes ahead (MOM's shell). The above substitution allows every parameter in (a), (b), (c), and (d) to be known virtually as well as MOM's lookahead as at ASF's lookahead. Therefore, the GS mathematical relationships are available to MOM.

An example of their usefulness to MOM is as follows:

> For certain possiblems 20 or 30 minutes in the future, the prediction uncertainties may be large enough that MOM finds no specific left or right maneuver option definitely available for either aircraft–because these options are constrained by the other aircraft (and, let us suppose, by that aircraft only). Assume also that the other four options (above, below, ahead, behind) are constrained (by additional aircraft, performance limitations, etc.). In this case, MOM finds (via the Section 4.3 techniques) no outs for either aircraft. However, MOM can apply the GS mathematical relationships to assure that a safe resolution exists (and a gentle one at that). It may not be clear (at MOM's lookahead) which aircraft needs to maneuver, or whether the maneuver will be right or left, but the key point is that some gentle, safe out will become available.

Another useful feature of GS for MOM is that GS can be applied iteratively, for sets of possiblems sufficiently separated in time. This feature is a result of GS's consideration only of parallel lateral offset maneuvers; these offsets, once attained (a process which takes about four minutes), restore the geometry as parameterized in (a) and (i). That is, the encounter angle, the relative speed, and the most pessimistic possible relative timing to intersection are all unchanged by a parallel offset maneuver.

For example, consider Aircraft C in Figure A-1 (identical to Figures 4-3a), with three possiblems (versus Aircraft B, D, and E). Suppose the three possiblems occur, respectively, 10, 20, and 30 minutes in the future. Suppose also that Aircraft B, C, D, and E all have no outs. However, suppose that C's left and right options are constrained only by Aircraft B, D, and E, and also that the left and right options of B, D, and E are constrained only by C. Then:

- Possiblem C-B can be resolved by a GS gentle parallel offset (by C or B).
- Possiblem C-D can be resolved by a GS gentle parallel offset (by C or D), regardless of whether or not C was maneuvered for the C-B possiblem.
- Possiblem C-E can be resolved by a GS gentle parallel offset (by C or E), regardless of whether or not C was maneuvered for the C-B or C-D possiblems.

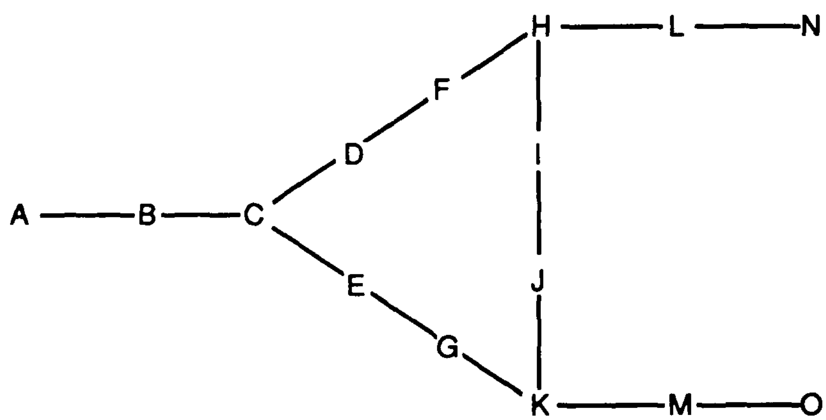

FIGURE A-1
A 15-AIRCRAFT, 15-POSSIBLEM CLUSTER

Despite the fact that none of the four aircraft have a specific out, MOM knows, thanks to GS, that sufficient outs will become available as needed, for these three possiblems.

A.1.3 Symbiosis Between MOM and GS

The preceding section gives examples of how MOM benefits from GS. MOM's ability to simplify complex clusters into isolated pairwise possiblems, in return, "benefits" GS (in the sense that GS can be applied only for pairwise interactions, the GS methodology assumes no third aircraft are present near the closest approach).

Figure A-2 summarizes the symbiosis. MOM helps to simplify clusters into isolated possiblems. GS then assures that gentle maneuvers suffice for the isolated possiblems. Since the maneuvers are gentle, the downstream impact of GS maneuvers is minimal. This helps maintain the integrity of MOM's data base, which MOM depends upon to continue to simplify clusters as time passes–the cycle is complete.

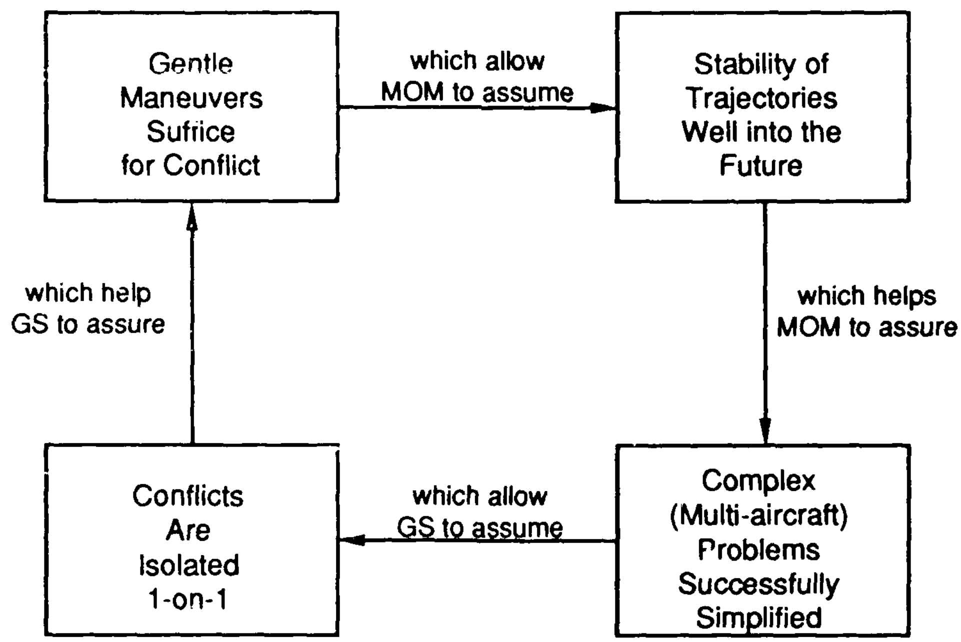

FIGURE A-2
SYMBIOSIS BETWEEN MOM AND GS

A.2 FUTURE OUTS: OUTS GUARANTEED AVAILABLE BUT WHOSE MAGNITUDE IS NOT YET PREDICTABLE

It is possible to predict the availability of outs in the future via means other than GS. GS, a mathematical characterization of parallel offset maneuvers as possible resolutions for the state space of pairwise linear encounters, does not apply to situations where an aircraft interacts simultaneously with more than one other aircraft. In these situations, a technique called Future Outs can often be applied.

The Future Outs algorithm[3] has little in common with the GS algorithm, but the results of both are applied in much the same way by MOM to simplify clusters. A future out (like a GS out) is a maneuver guaranteed early to work, whose displacement from nominal is bounded, but the exact details of the maneuver are not predictable early.

An example of a future out is as follows. Two aircraft, V and W, may be right of aircraft U's trajectory. If V and W end up close together, U can go right of both, but if V and W are well separated, U can go right of V but keep left of W. A rightward out is definitely available, but the magnitude of the displacement m is not predictable.

Another related future out situation concerns an out for which a particular displacement m is indeed guaranteed to work, but the smallest such m is quite large. However, it is predictable that some smaller m will work.

It is useful to expand on the above (U, V, and W) example, using specific numbers. As detected at time 8:00, Aircraft V might constrain Aircraft U's rightward displacements of $0 \leq m \leq 15$ nmi around 8:30, and Aircraft W might constrain U's rightward displacements of 7 <= m <= 27 nmi, also around 8:30. The smallest specific rightward displacement m guaranteed to avoid both possiblems is 27 mi.

In this example, it is assumed that other maneuver options (e.g., LEFT) are unavailable.

As time passes, and the boxes shrink, the range of constrained rightward displacements generally shrinks as well; the degree of shrinkage to expect can be predicted to some extent. By 8:15, V's constraints at 8:30 upon U's rightward displacements might shrink to, say, an eight-mile range, such as 0-8 nmi, 1-9 nmi, ..., or 7-15 nmi. Likewise, W's constraints upon U's rightward displacements might shrink to, say, a seven-mile range, such as 7-14 nmi, 8-15 nmi, ..., 20-27 nmi. Which of these possiblities materialize will be clear by 8:15, but at any time it is clear that only one of these possibilities can materialize. It can be seen that a rightward displacement of no more than 15 nmi (not 27 nmi) will be necessary. This 15-nmi displacement will be needed if V rules out the range 0-8, and W rules out the ranges 8-15 (so that U must go to the right of both V and W). Otherwise, some displacement less than 15 nmi will work. For instance, if V rules out 0-8 nmi (as before)

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[3]A generalization of the linear programming solution mentioned in Sections 4.2.1 and 4.2.2.

and W rules out 9-16 nmi, U may pass to the right of V but to the left of W, via m = 8.5 nmi. If V rules out 1-9 nmi, instead of 0-8 nmi, U need not maneuver at all.

The degree to which constraints on displacements m from nominal shrink as a function of encounter geometry and box-shrinkage is not yet well understood. In some geometries there is significant shrinkage; in others, none at all.[4] Analysis is underway to develop, if possible, a general theory to address this question (perhaps borrowing some techniques from the GS analysis).

Future outs are a relatively recent addition to the tools available to MOM. They have been studied in less detail than the MOM material discussed in Sections 1 through 6.

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[4]The boxes are 5-dimensional (variables are x,y,z, time, and displacement m--see Section 4.2.2), and are shrinking mainly in one dimension (time--the uncertainty in arrival time at a given point along an aircraft's trajectory). The question boils down to how the shrinkage of the two boxes in one dimension (time) affects the cross section of their intersection in another dimension (m).

APPENDIX B

SELECTION OF CONTINGENCY PLANS AND DESIGNATED OUTS

Section 4 and Appendix A discuss generic simplification of clusters (in which simplifications are detected but not evaluated versus each other); the discussion in this appendix shifts to determining which simplification (among the many possibilities) to select.

The material herein should be treated as somewhat speculative, as it has not yet attained the broad consensus achieved by the material in Sections 1 through 6 of this document. The key tradeoff in evaluating simplification strategies involves the interplay between:

- MOM's ability to look at the interrelationships between multiple possiblems, using relatively large lookaheads and prediction uncertainties.

- ASF's ability to fine-tune resolutions to simple (e.g., pairwise) problems, using relatively small lookahead and up-to-the-minute track data.

As mentioned in Section 3.2.4 and 3.2.5, there are two distinct roles that MOM is expected to play in AERA 3.

One role for MOM involves maintaining an evolving contingency plan (consisting of a set of outs, called contingency outs), that provides safe separation between all aircraft, over a specified lookahead horizon. A change to a contingency plan may be made (e.g., to meet a user request), but only if an alternate contingency plan can be found.

The other role for MOM involves selecting outs, called designated outs, which provide a high enough degree of planning benefits that AERA 3 should commit early to them, to some degree. There are several possible levels of commitment to a designated out.

Determining the degree to which AERA 3 commits to an out, either by incorporating it into the contingency plan, or by designating it, is one of the most important open issues needing to be addressed.

One can develop measure for how "good" an out is, in terms of planning benefits and benefits/costs to the user; it is generally true that the higher an out "scores" according to the measures, the higher the level at which it is attractive to commit to the out. Measures include:

- Number of possiblems the out resolves.

- Number of near-simultaneous possiblems the out resolves.

- Whether the possiblems resolved have a high probability of becoming actual conflicts requiring separation maneuvers.

- Cost of the out in terms of fuel and/or delay time (the lower the better).

- Whether alternative outs exist, and how those outs "score".

- Whether a Gentle-Strict out, or a Future Out, is likely or certain to become available (see Appendix A).

- Number of aircraft, possiblems, etc., in the cluster being simplified by the out (MOM tends to commit ever more readily to simplifying ever more complex clusters, other measures being equal).

In a typical AERA 3 scenario, contingency outs are expected to be relatively common, but designated outs relatively rare.

B.1 MOM'S CONTINGENCY PLAN

In its role as provider of a contingency plan, MOM establishes a set of contingency outs which, if actually incorporated into the aircraft trajectories, would allow safe separation for all the aircraft (from the current time out to a lookahead horizon), even assuming that prediction uncertainties combine as adversely as possible. Barring the most adverse combinations, ASF is generally expected to separate the aircraft using fewer and gentler maneuvers than would a contingency plan. Assuming trajectories for all aircraft are available, the contingency plan (being pessimistic) acts as a lower bound on how good a resolution ASF will come up with.

A key motivation for establishing a contingency plan is verification of AERA 3. Verification, a significant task in any ATC automation, is especially critical when the human is taken out of the loop for the first time, as in the inner shells of AERA 3. The contingency plan is MOM's means of fulfilling its role as described in Section 3.4–assuring that ASF can operate successfully in a global context, although ASF generally considers pairwise separation problems one at a time. If MOM is unable to establish a contingency plan, action by AERA 3's next outer shell (e.g., by Density/Complexity Manager) may be warranted.

MOM seeks contingency plans that involve as few contingency outs as possible, and whose contingency outs score as high as possible on the above list of measures.

Establishment of a contingency out represents an intermediate level of AERA 3 commitment to an out–less than designating, but more than nothing. AERA 3 focuses its planning efforts on the possibility that the contingency out (rather than alternatives) will be used, but does not forbid resolutions that are incompatible with a contingency out (if an alternate contingency plan can be found).

B.1.1 Incremental Changes To Contingency Plan

As time passes, the air traffic situation changes. Aircraft take off, enter or exit the geographical airspace under consideration; other aircraft experience unpredicted headwinds/tailwinds; still other aircraft receive resolution maneuvers (e.g., from ASF). The contingency plan must change to keep pace.

The simplest way for MOM to update the contingency plan is to let the plan evolve incrementally. A new aircraft may create or exacerbate a cluster and necessitate a new contingency out (not necessarily for the new aircraft). The same might happen if an aircraft experiences an unexpected headwind/tailwind. Another possibility is that ASF might resolve a conflict by maneuvering an aircraft into the airspace that would be used by the contingency out, necessitating the choice of a different contingency out(s) (note: if this possibility causes difficulties, the contingency out probably should have been designated, so that ASF would find some other resolution).

B.1.2 Systematic Changes To Contingency Plan

As future possiblems/clusters draw nearer in time, prediction uncertainties shrink. Maneuver options not previously available may become so, and previously available options may require smaller displacements from nominal. For instance, a leftward displacement for a given aircraft of 14 nmi may appear necessary 25 minutes out, but 15 minutes out it may be clear that at worst a 10 nmi leftward displacement is necessary. To capitalize on this phenomenon, it is expected that MOM will, at intervals (perhaps every few minutes) effect systematic (rather than incremental) changes in the contingency plan. (Note that Appendix A discusses predicted shrinkages, whereas the topic in this appendix is observed shrinkages.) MOM periodically considers the impact of dropping all its contingency outs (but not its designated outs). Some set of clusters would result. A new contingency plan would be created from scratch. The selection of each successive contingency out would not be based on the assumption that other aircraft follow aged contingency outs selected perhaps five or ten minutes earlier (as is the case for incremental changes discussed in Section B.1.1). Instead, each successive contingency out is based on all the other aircraft following either nonmaneuvered trajectories or freshly-established contingency outs.

If no better contingency plan is found (involving fewer or gentler outs), MOM can always revert to the original contingency plan. Normally, however, the new contingency plan (for a given set of trajectories) should be better than the old one, and therefore form a tighter lower bound on ASF's performance.

For a given future cluster, one can envision MOM developing a series of better and better contingency plans involving fewer (and gentler) contingency outs. ASF's solution can be thought of as the final stage in the process.

B.1.3 Example Contingency Plan

A contingency plan for the cluster in Figures B-1 (identical to Figure 4-3a) might involve, first of all, contingency outs for Aircraft C, H, and K (some or all of these may qualify as designated outs, but for the example, assume not). Then, for each of the six isolated possiblems remaining (A-B, D-F, E-G, I-J, L-N, and M-O), MOM would have to assure that one of the aircraft in each possiblem has at least one out, and that all nine outs (those for C, H, K, A-B, D-F, E-G, I-J, L-N, and M-O) are mutually compatible as described in Section 4.6. Note: a GS resolution would suffice for any of the one-on-one possiblems, even if neither aircraft has an out as defined in Section 4.3.

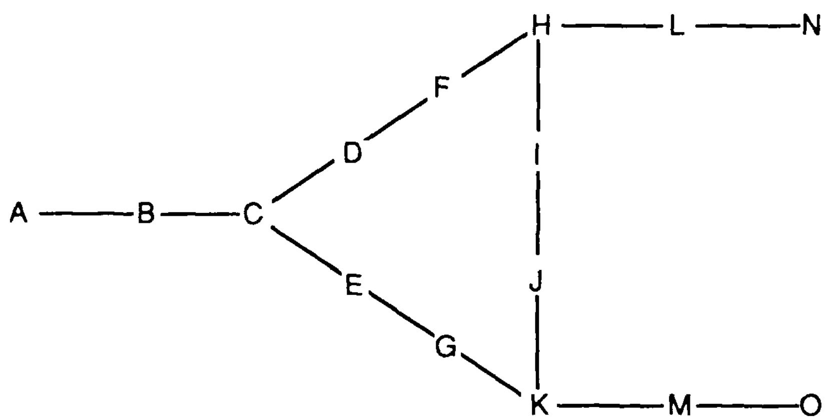

FIGURE B-1
A 15-AIRCRAFT, 15-POSSIBLEM CLUSTER

Such thorough checking for contingency plans is probably appropriate for short lookaheads (perhaps up to 15 minutes in the future).

The exact amount of stringency needed in testing the contingency plan is a current area of research via simulation. It is closely related to the open questions involving designating, discussed next.

B.2 DESIGNATED OUTS

Besides maintaining a contingency plan, MOM identifies certain outs, called designated outs, which provide enough planning benefits that AERA 3 should commit early to them, despite the fact that they address problems ten or more minutes in the future about which more accurate information will be available later (e.g., to the ASF shell).

When an out is designated, it is treated by MOM as if it were the aircraft's actual plan. Subsequent planning (including subsequent designated outs and contingency planning) assumes the aircraft will perform the designated out. However, some details of the designated out may be deferred (to ASF).

A current area of active research is to determine rules to select which outs to designate. The primary consideration, of course, is that the benefits of committing early to an out (in terms of smoother traffic flow, simpler clusters, ability to resolve multiple possiblems with a single maneuver, pruning of the decision tree to stabilize planning, and minimization of domino effects that might occur if pairwise problems are dealt with one at a time) outweigh the cost (of committing while significant predicted position uncertainties remain).

B.2.1 Levels of Commitment To A Designated Out

There is a hierarchy of possible levels of commitment to a designated out, labeled (from least to greatest commitment) recommended outs, earmarked outs, and specified outs.

B.2.1.1 Recommended Out

A recommended out is an out that is recommended by MOM for use by ASF, but which ASF may reject if ASF finds a better resolution.

A recommended out differs from a contingency out in that it (like all designated outs) is not modified further by MOM (as are contingency outs, as described in Section 6.1.2).

A typical recommended out is one that yields significant planning benefits (such as solving several possiblems at once, thereby simplifying a large cluster), and scores highest among several alternative outs.

Recommended outs appear ideal in relatively low density traffic. Suppose there are several aircraft in a cluster, but no other traffic nearby or downstream. User benefits may be optimized via deferral of a final decision to ASF. But ASF should be informed by MOM of any especially attractive resolutions.

In denser traffic, where the resolution for early clusters may affect resolutions for later clusters, higher levels of commitment to outs by MOM may be advisable in order to stabilize planning.

B.2.1.2 Earmarked Out

An earmarked out is an out which (MOM declares) must be used (by ASF), although the details of the implementation (e.g., timing and exact magnitude of displacement from nominal) are deferred to ASF. For instance, at time 2:20, MOM could earmark an rightward out for Aircraft B, of roughly 10 nmi, starting roughly at 2:30. At 2:28, ASF would clear, perhaps, an 8 nmi rightward displacement to begin at 2:31 (the gentlest rightward out it can find, based on the latest track data).

One type of out which might be earmarked is one which scores significantly higher relative to its alternatives, and/or has no reasonable alternatives.

Another type of out which might be earmarked is one that does not score exceptionally high, but which is considered to be "good enough" to merit an early MOM commitment, in order to prune the decision tree (MOM must avoid trying to keep track of too many combinations of possible resolutions, that might proliferate if MOM too often takes no action, or only recommends an out to ASF).

B.2.1.3 Specified Out

As specified out is an out whose implementation is specified exactly by MOM; ASF does not alter it based on track data.

A specified out might be useful in a situation where there are two already established earmarked outs and it is desired to earmark a third out, which threads between the first two. If ASF is allowed to make modifications to the two established earmarked outs (even fairly minor modifications), there may be no room left for the third out to thread between them. A solution might be for the two established earmarked outs to be declared specified outs, thereby assuring room for the third out. The third out could be earmarked rather than specified; there is no harm in allowing ASF in this case to find the gentlest path between the two specified outs.

B.2.2 Some Guidelines In Designating Outs

Various measures for evaluating outs in general are listed at the beginning of this appendix. Several other criteria are worth discussion in the specific context of evaluating rules for designating outs.

MOM may designate an out which provides a partial resolution. Suppose there are possiblems 10 minutes in the future for which 10 miles leftward suffices, and possiblems 20 minutes in the future for which 20 miles leftward suffices. MOM might designate 10 miles leftward (displacement to begin 6 minutes in the future), with possible (non-designated) further leftward maneuvering, if necessary, 16 minutes in the future.

Some outs, particularly AHEAD outs, require a maneuver to begin well in advance of the possiblem(s) to be resolved (since aircraft often can increase their speed only slightly). If no early commitment is made, the out is lost; it may therefore be necessary to designate the out.

Sometimes it may be obvious that a particular aircraft should be maneuvered at a future time, but not yet obvious which out to use; it may be advisable to delay designating. At other times, it may be obvious that some aircraft must maneuver in a particular direction, but it is not obvious which aircraft should maneuver (e.g., heavy traffic at one flight level, sparse traffic at the next lower flight level). Again, it may be advisable to delay designating.

B.3 SUMMARY

There is a hierarchy of possible levels of commitment by MOM to a given out.

First, MOM may make no commitment to a particular out. The existence of the out is nevertheless useful (e.g., MOM seeks to assure that each aircraft have at least one out).

A low level of commitment by MOM to an out is to make the out a part of MOM's contingency plan. The contingency plan, maintained at all times by MOM, is a set of outs which, if cleared, would put all aircraft on trajectories such that AERA's inner shell can separate them (e.g., all aircraft are free of possiblems). MOM's contingency plan changes over time, but at any one time all its outs are mutually compatible.

A higher level of commitment by MOM to an out is known as designating. As part of its ongoing planning, MOM assumes that a designated out will be cleared (although ASF is left some varying degree of freedom to alter the maneuver, if desirable). ASF's freedom depends on whether the designated out is classified as recommended, earmarked, or specified.

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